

ELECTRON SPECTROSCOPE WITH EMISSION INDUCED BY A MONOCHROMATIC ELECTRON BEAM

The present invention relates in general to spectroscopy and more in particular to systems of spectroscopic investigations based on the analysis of the energy
5 distribution of electrons emitted by a sample suitably excited by irradiation.

Electron spectroscopy analysis is one of the most important techniques of investigation of solid materials.

Basically there are two types of spectroscopy system, each with peculiar characteristics and potentialities; namely the Auger systems and the XPS (X-rays
10 Photoelectron Spectroscopy) systems.

Both kinds of systems are based on detecting the kinetic energy of electrons emitted from the surface of the sample subjected to bombardment with electrons or irradiation with X-rays.

The energies of electrons emitted from the surface of the sample are
15 characteristics of the elements and/or compounds present at the surface of the sample.

The Auger systems permit to inspect microareas of the sample surface down to a minimum linear dimension in the order of hundreds of nm and allow also a SEM (Secondary Electron Microscope) visualization of the inspected area by scanning
20 the area of acquisition of spectrometric data with the focused electron beam.

These systems have the drawback of permitting exclusively an elementary analysis. In other words, they are generally incapable of providing information on the chemical state of the identified elements because of the relatively weak chemical shift to which the Auger electron is subjected.

25 By contrast, XPS systems offer the possibility of gathering information also on the chemical bonds besides those on the Auger electron.

However, the XPS systems do not permit to restrict the area of inspection beyond minimum linear dimensions in the order of hundreds of μm , because of the difficulty of focusing X-ray beams.

Because of this limitation, this technique is hardly suited to conduct inspections
5 on microstructures, such as for example the typical microstructures that are defined by modern fabrication processes of integrated circuits.

Moreover, XPS systems generally do not permit to visualize the inspected area from which spectrometric data are acquired because the X-rays do not lend themselves to be used for scanning the area. Visualization is possible, but at
10 present the common approach remains that of using a dedicated auxiliary SEM column for visualizing the area through the secondary emitted electrons. However, this auxiliary visualization approach is not rigorously tied to the exciting X-ray beam directed on to the sample for the analysis, being the exciting sources distinct.

15 It is evident the need and usefulness of a spectroscopic investigation system capable of yielding information also on the chemical state, alike a XPS system, but which at the same time would allow to carry out investigation on microspot, that is on areas of submicrometric linear dimensions, similarly to what is possible to do with the known Auger systems.

20 To this pressing need the present applicant has found an effective answer.

It has been found that it is possible to obtain reliable information on the chemical state, that is on the energy of the chemical bond of an element, by analyzing the kinetic energy distribution of electrons emitted from an irradiated sample, by causing emission of electrons by irradiating the microarea of interest with a
25 substantially monoenergetic electron beam.

Notably, the chemical bond energy (BE) is given by the following relationship :

$$\text{BE} = h\nu - KE - \Omega \quad (1)$$

where $h\nu$ is the energy of the incident particles or photons, KE is the kinetic energy of the emitted electrons and Ω is the extraction energy.

Of course, the higher the resolution of the $h\nu$ term the more accurate will be the information on the chemical bond.

- 5 The present applicant has found that a beam of sufficiently energetic electrons that may be focused on a relatively small area of interest (microspot) of the surface of the sample, may be obtained by using a Field Emission Gauge (FEG) source of electrons and an appropriate energy filter (monochromator) capable of ensuring an energy resolution practically comparable to that of an X-ray monochromator.
- 10 Compared to the known systems using a focused electron beam such as the SEM, TEM, Auger and alike systems, all characterized in that they normally use thermo-ionic electron sources (hot sources), such as for example a hot tungsten source or a hot LaB_6 source, there are others electron sources ideally suited to applications requiring a high spatial resolution. Field emission electron sources
15 such as the so-called Schottky and "cold-cathode" sources have dimensions that generally are comprised between few nm, in the case of cold-cathode source, and about 15 nm in the case of Schottky sources. These dimensions are far smaller than those of the commonly use hot tungsten or LaB_6 sources that are in the order of at least 10.000 nm and normally much larger.
- 20 In addition, Schottky emission and cold cathode emission sources have the advantage of a much reduced energy dispersion of the emitted electrons, generally less than 1eV and a high brightness, that may be even several orders of magnitude greater than that of the hot cathode sources of LaB_6 or tungsten. Generally the brightness of Schottky or of cold cathode sources is greater than $10^8 \text{ A/cm}^2 \text{ SR}$.
- 25 For the objectives of the present invention, a Schottky source is preferable compared to a cold cathode source because a Schottky source, beside the low energy dispersion characteristic and high brightness, is far more easy to use and has an outstanding short term stability of the electronic current of the beam, which

is generally lower than 1% RMS.

Moreover, for the objectives of this invention, it is essential to employ an energy filter of the electron beam being focused on the surface of the sample under examination.

- 5 Energy filters are often called "monochromators" and their figure of merit is the smallest energy dispersion they are able to ensure in the filtered beam, such to convey on to the sample to be analyzed a focused electron beam having substantially a planar wave front.

- 10 The known techniques for monochromatizing an electron beam are several. Most commonly, the approach is that of applying a magnetic-electrostatic correction of the trajectory of an electron traveling through a certain spatial region that may be semispherical (HEA, "Hemispherical Energy Analyzer") [1] or having a quadruple structure (Wien filter, possibly in cascade) [2], [3], known also as "mandolino" [4], or as typically implemented in transmission electron
15 microscopes (TEM) for conducting a EELS (Electron Energy Loss Spectroscopy) studies ("troncoidal monochromator TM")[5], wherein, always by means of electromagnetic lenses, electrons of a defined kinetic energy are gathered and exit the monochromator.

- 20 There are innumerable monochromator filters for electron beams described in literature. Basically all these filters are based on the principle that electrons that do not possess the selected kinetic energy are electromagnetically deflected over different trajectories from the trajectory of electrons having the desired kinetic energy, which normally coincides with the central axis of the deflecting device. The deflected electrons are eventually suppressed by collecting them on a
25 collector, or in some cases electrons are re-focalized by guiding them along an appropriately designed path so that they emerge from the spatial sector relative to the desired kinetic energy value.

It has been found that the energy dispersion in the electron beam that may be

obtained by employing such a monochromator filter for electron beams may be practically reduced to a fraction of eV and that under such conditions the so monochromatized electron beam is suitable to produce the required analytical results.

- 5 Even the level of electronic current that may be obtained through these monochromators, which normally may reach up to about ten nA, is satisfactory for the objectives.

- The novel spectroscopic system of this invention besides its ability to determine the chemical bond existing among elements present on the microarea scanned by
10 the monochromatic electron beam of excitation of the sample permits also to visualize the scanned area in a way that is perfectly similar to what happens in a known Auger system, which by contrast is unable to provide information on the chemical state of the detected elements.

Figure 1 is a basic diagram of the spectroscopic analysis system of this invention.

- 15 **Figures 2, 3 and 4** are spectrograms obtained from preliminary tests that demonstrate the effectiveness of the novel method of this invention.

Figure 1 is a basic diagram of an electron spectroscope implementing this invention.

- The field emission electron source is preferably a Schottky emission source, for
20 example it may be of the type produced by the company FEI of the Philips group or by the Japanese company Denka.

- The monochromator energy filter of the focused electron beam may be any commercially available filter capable of ensuring a maximum energy dispersion of the electrons of the beam exciting the filter of less than 0,2 eV, and more
25 preferably less than 0,1 ev.

The so filtered electron beam is directed on the surface of the sample to analyze.

The irradiated area may have linear dimensions as small as in the order 100 nm and even less.

Of course, scanning of a certain area of the sample is done as in any other known focused electron beam system.

- 5 The analysis of the kinetic energy spectrum of the electrons emitted from the excited area of the sample is carried out with a common spherical capacitor energy analyzer.

- 10 Decelerating and focusing means of electrons emitted from the excited area of the sample for producing a spectrum representatives of the distribution of the kinetic energies of the emitted electrons over an inlet aperture of said energy analyzer, a detector for detecting the electrons traveling through the energy analyzer for reproducing the distribution of the kinetic energies of the emitted electrons along at least a direction orthogonal to the radial direction of said spherical capacitor of the analyzer.

- 15 Preliminary tests have been conducted on SiO₂ and Ti samples and the results as shown in Figures 2, 3 and 4.

- 20 The validity of the novel approach of the applicant was demonstrated by a number of laboratory tests that have been carried out using the available commercial micro Auger system of Physical Electronics, Model 670, notwithstanding that, as the normally available systems of this type, it was equipped with a common electron source of ZrO₂ coated tungsten. The machine had and a CMA (Cylindrical Mirror Analyzer) detector, coaxial to the incident electron beam. That is a proof of the validity of the novel technique was sought notwithstanding that a recognizably more effective apparatus using an electron source of reduced energy dispersion was not available.
- 25

Different electron accelerating voltages were used, respectively of 3.5 and 3.0 kV, with electronic current of about 10nA, in order to place in evidence the shift of the

detected peak upon the varying of the accelerating voltage, in order to demonstrate the dependence of the position of the peak in the spectrum from the accelerating voltage of the exciting beam.

For a first test a sample of ultra pure SiO_2 sample of 100 nm of thickness,
5 produced by thermo deposition on silicon has been used and the sample has been analyzed without any prior cleaning of the surface neither by chemical cleaning solutions or ion bombardment.

By observing the obtained spectrogram reproduced in Figure 2, it may be noted that with an electron beam accelerated at 3.5 kV, a peak appears at 2,970 eV
10 which, from the relationship (1), yields a BE of 530 eV.

The precise value of the extraction energy (Ω) term should eventually be determined experimentally using appropriate calibration samples. For the purposes of these preliminary tests, the value attributed to it was considered to be a first approximation, missing an absolutely precise value of the term Ω
15 (determined by specific tests) to be used in equation (1), nevertheless the result appeared to be very close to the known BE of the oxygen core level 1s, which in SiO_2 is reported in literature to be of about 533-534 eV. [6].

As commonly done in an Auger system, the spectrum was numerically differentiated in order to give more emphasis to the neighborhood of the detected
20 peak.

In order to further demonstrate the validity of the novel approach, a different sample of ultra pure titanium deposited on SiO_2 has been used. The sample showed the presence of a superficial film of native titanium oxide.

The spectroscopic analysis was carried out under the same experimental
25 conditions of the preceding test, that is at the same accelerating voltage and electronic current, using the same commercially available apparatus, without any cleaning of the sample surface.

The obtained spectrogram is reproduced in Figure 3. It may be noted that, with an accelerating voltage of 3.5 kV, a definite peak appears at 3,054 eV, which from the relationship (1), using a first approximation value for the term Ω , yields a BE of 446 eV.

- 5 Even in this case the exact value of the term Ω was not determined, therefore the attributed value of BE is just a first approximation estimate that comfortably compares with the value of Ti Core 2p 3/2, that in literature is indicated as being equal to 453-454 eV [6].

- 10 Even in this case, a numerical differentiation of the spectrum has been introduced for better detailing the zone of interest.

Finally, it has been proved that the novel test model remains valid not just among different materials but also upon the varying of the accelerating voltage of the exciting electrons. For this purpose the same Ti sample used in the preceding test has been used lowering the acceleration in voltage from 3.5 to 3.0 kV.

- 15 If the test model of this invention is valid the expectation is that also the peak shift by a difference equal to the energy difference of the exciting electron beam.

- 20 As may be clearly observed in Figure 4, the result of this further test has been that of an estimated BE of 451 eV, to be compared with the value reported in literature 453-454 eV [6]. Compared to the preceding test, a change of about 5 eV in the estimated value of the BE is observed (in the preceding test the BE was found to be 446 eV), at the changed accelerating voltage. However, it is to be considered that by decreasing the accelerating voltage the probability of ionizing the substrate decreases, thus implying a lowering of the intensity of the detected signal together with a dispersion thereof. Moreover, it is also possible that by varying the
25 accelerating voltage by 500 eV, the Ω function, may itself vary, being this parameter dependent on the system in its whole.

Notwithstanding the fact that the tests have been carried out using a commercially

available apparatus (an Auger system employing a hot cathode electron source) therefore not optimize for the novel test approach of this invention, from these tests it may be reasonably deduced that the substrate, whichever it is, has reacted to the external electron excitation by emitting a signal (emitted electrons) that
5 appears to carry information on the superficial chemical state of the detected elements, proving the validity of the inventors assumptions.

Due to these relative rudimentaryness of the tests, it has been impossible to obtain signals of relatively large managed to be confirmed with higher precision as aligned with the expected data from the literature, however the evident good
10 approximation of the estimate such as obtained with the rudimental (not fully optimized) apparatuses in the case at upon an appropriate design phase, the novel technique of this invention will usefully inscribed itself among the known techniques (Auger, EELS and XPS), characterizing itself as being able to produce useful information on the chemical state of the detected elements without the
15 limitations of the size of the inspected area of comparable known systems.

BIBLIOGRAPHY

- [1] D. Muigg, G. Denifl, A. Stamatovic, O. Echt, T.D. Maerk, Chemical Physics, 239 (1998) 409-416.
- [2] E. Plies, J. Baertle, A. Huber, Europaeische Patentanmeldung EP 1 220 292
5 A2 (2002).
- [3] E. Plies, J. Baertle, Microsc. Microana., Vol. 9 (suppl. 3) 028 (2003).
- [4] E. Essers, B. Huber, Microsc. Microanal. Vol. 9 (suppl. 3) 020 (2003).
- [5] V. Grill, H. Drexel, W. Sailer, M. Lezius, T.D. Maerk. J. Mass Spectrom., 2001; 36: 151-158.
- 10 [6] Handbook of X-ray Photoelectron Spectroscopy, Physical Electronics, Inc., 1995, ISBN: 0-9648124-1-X